$\mathcal{E}$uropean $\mathcal{C}$onnection

M. Margarete Mühlleitner
(CERN/LAPTH)

$\mathcal{MC}4\mathcal{BSM}$ Fermilab, March 20-21, 2006

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$\mathcal{O}$utline

- ⋆ What's a tool and what it takes to make one
- ⋆ Contributions to MC4BSM
- ⋆ How tools talk to each other - e.g. SLHA
- ⋆ Tools 2006 - LAPTH-LAPP 26-28 June 2006

$\mathcal{A}$bout $\mathcal{T}$ools

$\mathcal{L}$BSM Models

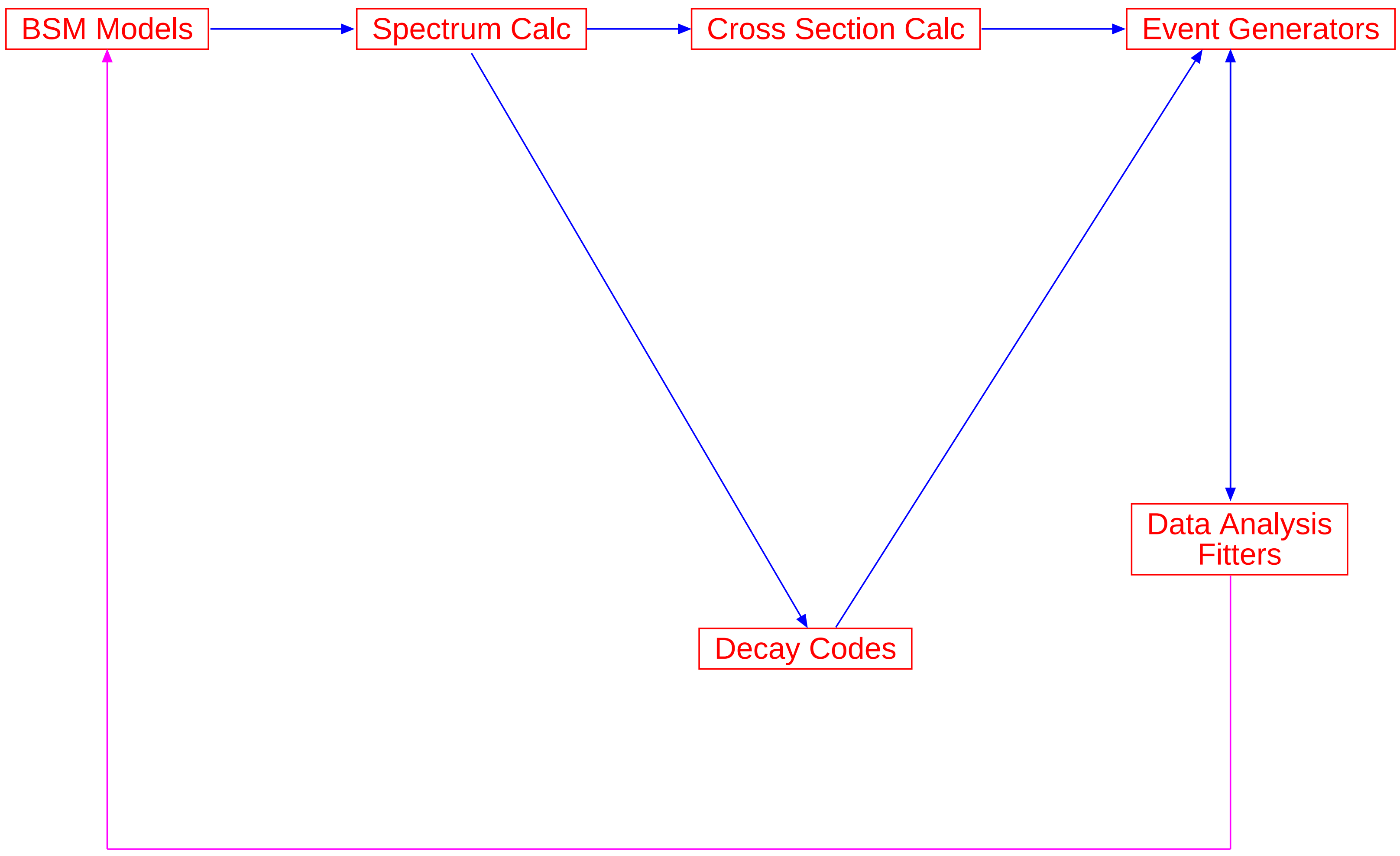
TOOLS

Experimental discovery and data analysis

$\mathcal{A}$bout $\mathcal{T}$ools

BSM Models —— **FINAL AIM** ——→ Event Generators

About Tools


BSM Models
Spectrum Calc
Cross Section Calc
Event Generators
Data Analysis
Fitters
Decay Codes

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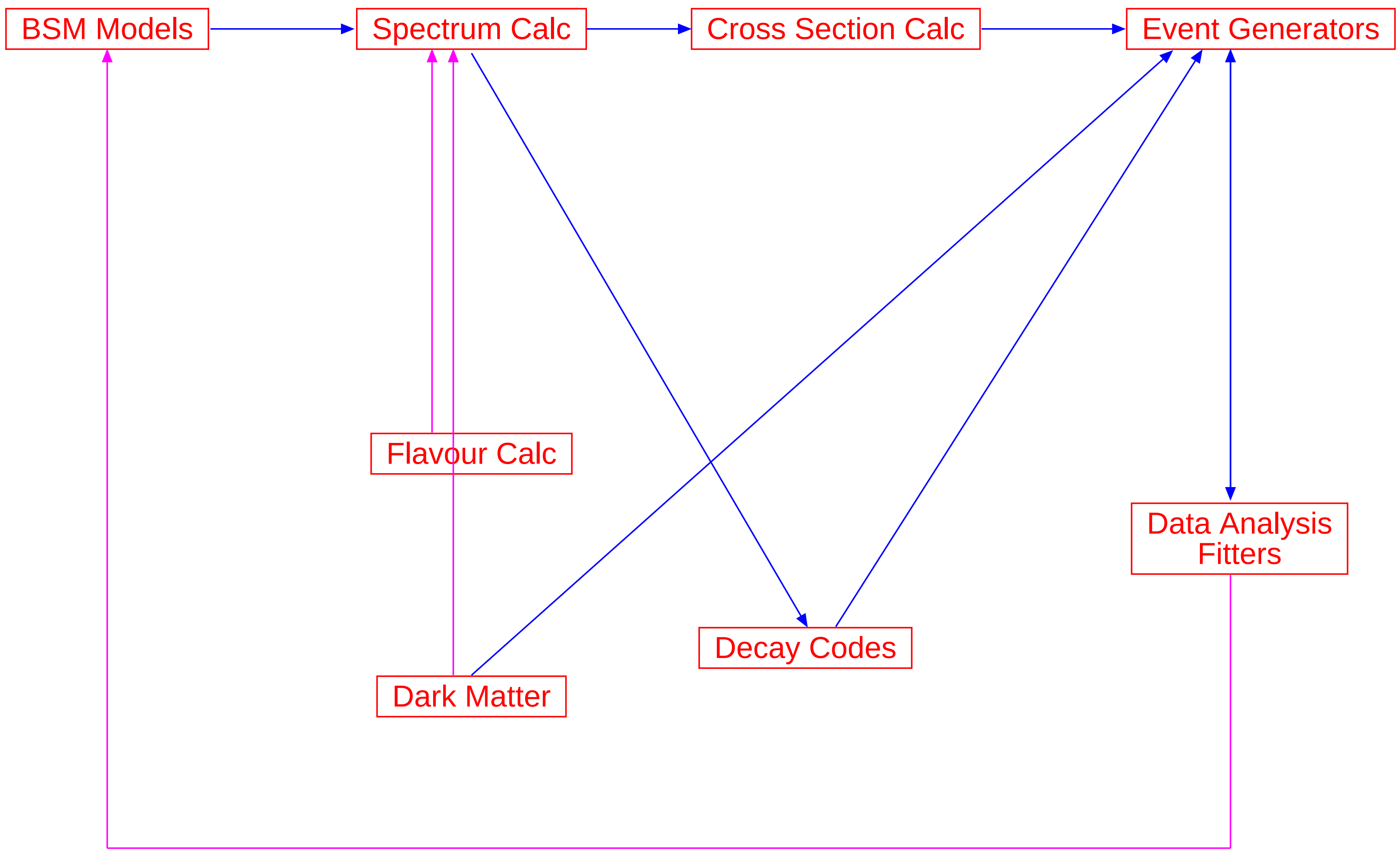

BSM Models
Spectrum Calc
Cross Section Calc
Event Generators
Flavour Calc
Data Analysis
Fitters
Decay Codes
Dark Matter

About Tools

BSM Models

- (N)MSSM
- CPV, RPV
- Ext $H, \tilde{\chi}^0$ sectors *Langacker
- NS Higgses *Kaplan
- Little H *Belyaev, Hubisz,Schmaltz
- Twin Higgs *Su
- Higgsless,Z' *Simmons
- Warped ED *Agashe
- Warped/Comp. Pheno *Sundrum
- UED *Cheng
- KK↔SUSY *Yavin
- Top Partners *Reece
- ...

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- `CPSuperH`
- `FeynHiggs`
- `NMHDECAY`
- RGE Codes
  `Isasusy`
  `SoftSusy`
  `Spheno`
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- 1-loop/General
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- `ALPGEN` - `VECBOS`
- `WHIZARD` ...
- SCET→MC's *Schwartz

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- `Bard` *Knuteson,Mrenna
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- `Sfitter`
- `NP-LHCFast` *Walker
- Requs. from the exp. *de Roeck

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Flavour Calc

- $(g-2)_\mu$
- $b \to s\gamma$
- $B_s \to \mu^+\mu^-$
- ...

Dark Matter

- `micrOMEGAs`
- `SloopS`
- `DARKSUSY`
- Relic density
- `NeutDriver` ...

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$\mathcal{L}$

Feynman rules
(Eff. Pot.)

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SM Bkg/Gen

Albert de Roeck "Exhortation"

Issues for Extra Dimension analyses for expermimentalists

- ▷ include processes in MC Generators
- ▷ include complete information in MC Generators (spin correlations $\rightarrow$ SUSY$\leftrightarrow$UED,...)
- ▷ cross checks between codes/Monte Carlos
- ▷ agree on phase space available for BSM at future exps. (constraints from other data)
- ▷ benchmark scenarios
- ▷ precise knowledge of the SM background
- ▷ higher order corrections
- ▷ formalism unification

Organization:

- this workshop MC4BSM
- EuroGdr
- Tools for SUSY and the New Physics
- TeV4LHC
- Les Houches ($\rightsquigarrow$ SLHA)

Tools Repository: `http://www.ippp.dur.ac.uk/montecarlo/BSM/`

Kaustubh Agashe

“Signals for a Warped Extra Dimension”

- **Warped Extra Dimension** $\rightarrow$ Planck-weak scale hierarchy problem, grand unification, dark matter candidate, ...

- **Kaluza Klein modes:** SM fields have excitations in the ED, appearing as heavy particles from the 4D point of view:

- **Signals at LHC: Direct Production of KK modes**

  (i) “Single” Production of SM KK modes (few TeV) $\rightsquigarrow$
  Excess of “right”-handed top pairs and W/Z’s.
  Angular distribution of top decay products: discriminating feature.

  (ii) KK GUT partners of top ($\lesssim$ 1 TeV) provide a dark matter candidate (ν'_R).
  Pair production of charged partners of DM decay into DM and typically top $\rightsquigarrow$
  Missing Energy + Leptons or Jets.
  Fake SUSY, differ in e.g. angular distributions or number of W’s.

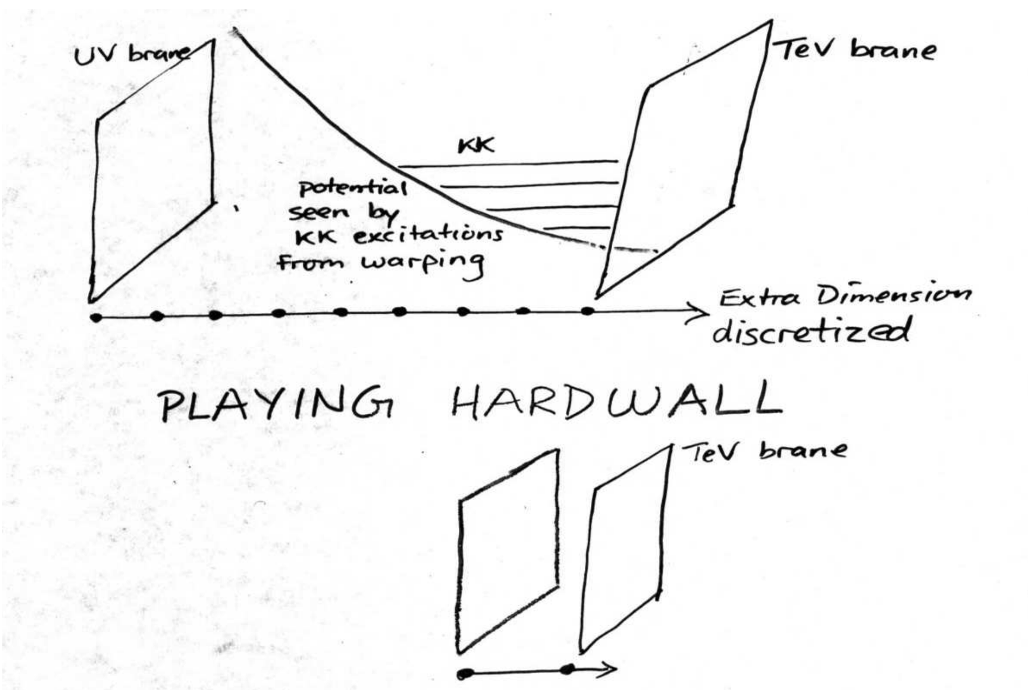
Raman Sundrum

“Warped/Composite Phenomenology (Over-)Simplified”

Reconnaissance Tool for TeV Scale

- ▷ Simple computations
- ▷ Broad view of particle physics, multiple channels
- ▷ Easily tinkered with
- ▷ Economical structure
- ▷ Easily compared to other scenarios
- ▷ 75% right

⇒ A coarse deconstruction of warped/composite scenario



Developing safe, interesting, representative versions

Martin Schmaltz **"Little Higgs Models"**

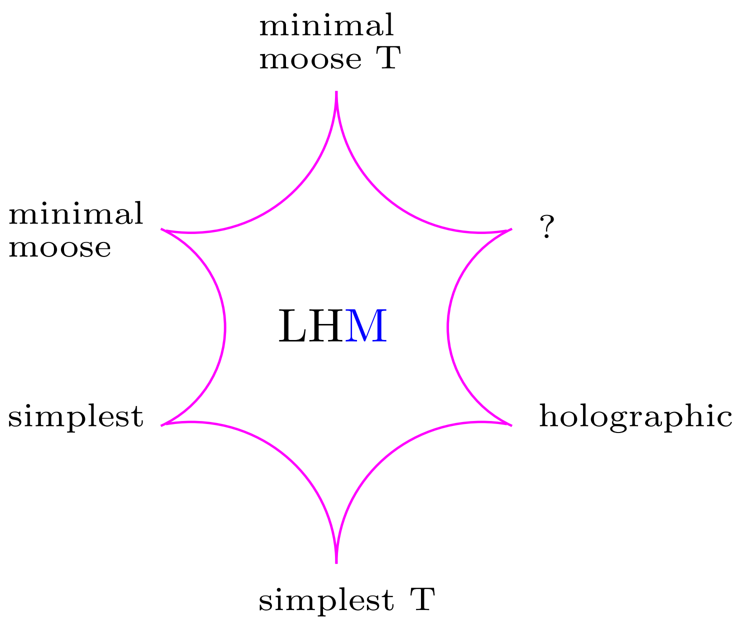
Motivation: Quadratic divergences at 1 loop in SM

General features: New bosonic symmetry $\rightsquigarrow$ "L.H. partners", coupling relations

T-parity: No tree level precision EW $\rightsquigarrow$ no tuning

Pheno: Pair prod, cascade decays, missing E_t, DM

"Little Higgs M-Theory" (Cheng,Thaler,Wang)



One Lagrangian in Monte Carlo:
different parameters $\rightsquigarrow$
simulate different models

Peter Richardson “HERWIG and PYTHIA”

`HERWIG`, `PYTHIA`: Monte Carlo Event Generators

Monte Carlo Event Generators: Programs which, starting with some fundamental process, predict the stable particles which will interact with a detector.

How to implement new models? Paradigm change 2001

Les Houches Accord in 2001: Agreement on a method of passing information between programs generating partonic processes and general purpose event generators - based on a common block. (Implemented in `HERWIG` and `PYTHIA`.)

Implementation of a new process in a generator: “Do it yourself using the Les Houches Accord”

Tutorial to help with this:
`http://www.ippp.durham.ac.uk/montecarlo/leshouches/tutorial/`

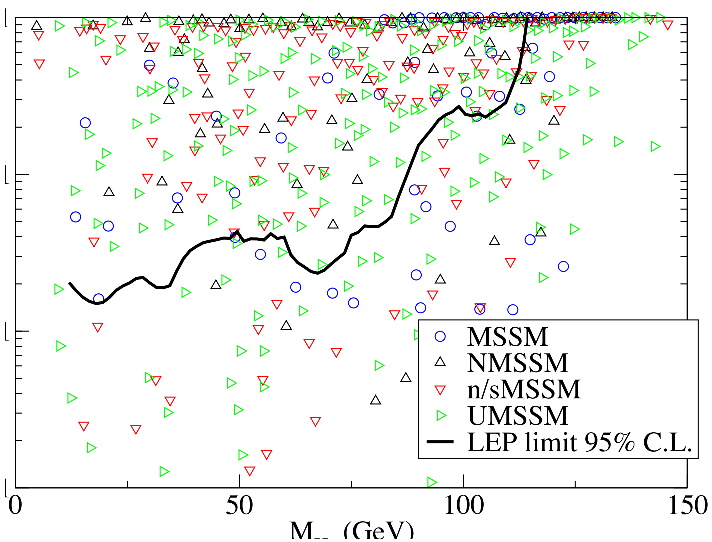
`HERWIG++`: C++ helicity library is used for all matrix element and decay calculations.

→ Easier coding of new matrix elements for production and decay.
→ Easy to do spin correlations (access to unaveraged matrix elements)

"Higgs, neutralinos and exotics beyond the MSSM"

- From the bottom up (top down): there may be more at TeV scale than (minimal SUGRA) MSSM (e.g. Z', extended Higgs/neutralino, quasi-chiral exotics)
- Dynamical μ term leads to very rich Higgs/neutralino physics at colliders and for cosmology

Experimental LEP SM and MSSM bounds may be relaxed by singlet-doublet mixing



- **Reduced ZZH_i coupling**

$$\xi_{ZZH_i} = (R_+^{i1}\cos\beta + R_+^{i2}\sin\beta)^2$$

- **Also, $X \to HA$, Z width, $\chi^\pm$ mass, $Z - Z'$ mixing, V minimum, RGE**

Pheno can be very different
Incorporation in codes!

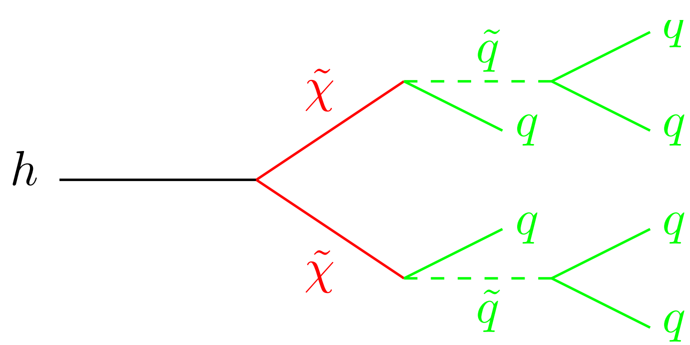
“Non-Standard Higgses in SUSY”

$h \to Njets$ in SUSY

LEP Bound on SM Higgs: 114.4 GeV.

Both SUSY and EW Precision Data prefer a lighter Higgs.

Add $\not{B}$ or new singlets to the MSSM, and the Higgs could dominantly decay to multiple jets.



Bound reduced to 82 GeV.

Invisible at the LHC?

New LEP II analysis and Tevatron studies might cover this blind spot.

Devin Walker

“New Physics with LHCFast”

LHCFast A toolkit to efficiently/quickly go from theories to collider observables.

- Consists of three parts:
  LHCFast1: Calculates matrix elements etc.
  LHCFast2: Imports matrix elements to showering generators.
  LHCFast3: Converts histogrammed data to plots.

- Improvements compared to existing packages:
  - Functionality/speed increases when going from Lagrangian to plots
  - Input of full helicity information possible
  - Upgrades not necessary (if Les Houches Accord, batch run commands remain the same)

Littlest Higgs with T-parity: discrete symmetry to ameliorate the “Little Hierarchy Problem”
- Viable Dark Matter Candidate
- Similar to R-parity in the MSSM
- New T-odd particles, transforming as $P_{\text{odd}} \to -P_{\text{odd}}$
- Simulation: $T_{heavy} \to t + A_{heavy}$, A_{heavy} DM candidate

Will become public after some more tests.

Matthew Schwartz

“Improving Event Generators using SCET”

- BSM physics: simulate accurately the SM background
- Different approximations in different event generators $\rightsquigarrow$ difficult to estimate the errors.
- QCD calculations involve logarithms of many scales
- **Soft Collinear Effective Theory** separates naturally the scales:
  - predictions can be systematically improved
  - consistent perturbation expansion
  - errors can be estimated

Eliminate a lot of guesswork in trusting MC programs.

Reduce one of the dominant sources of uncertainty in event generation.

Michael Peskin

“BSM processes with Pandora”

provide a toolbox for creating event generators for general physics processes
extensible code that makes it easy to change particle couplings and decay chains
full accounting of (longitudinal) polarization

- Originally developed for NLC/ILC studies
- Pandora: parton level event generator in C++ with an interface to `PYTHIA` hadronization
- Interface with `Tauola` to generate long. polarized τ decays

To Do

▷ inclusion of $e^+e^- \rightarrow$ SUSY processes and decays and test the underlying structure

▷ inclusion of UED by generalization of the SUSY classes

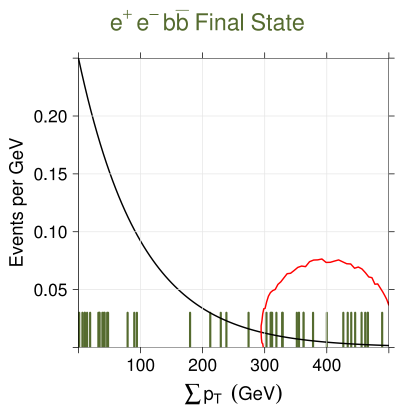
▷ construction of beam (parton density) classes for pp collisions

▷ implementation of Les Houches Accord, full color connection structure in LEvent and pandora_pythia

Stephen Mrenna

"BARD"

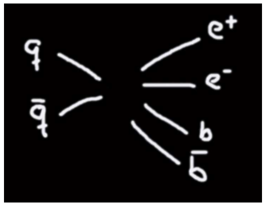
Bottom-Up Algorithm
to explain an observed discrepancy in the data

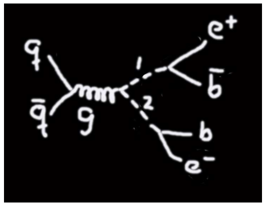


BARD's starting point: Excess in data

Determine new terms describing best observed discrepancy:

$\mathcal{L}_{\mathcal{H}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{new}}$





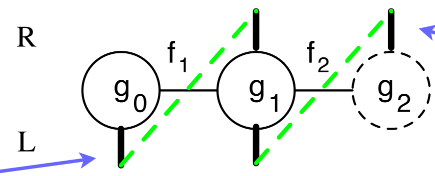
Bottom-Up Approach: BARD able to perform more targeted search than those scanning model parameter spaces

Elizabeth Simmons

“Two Brief Sketches: (1) Higgsless Models (2) Z' preferring the 3rd generation”

A Simple 3-Site Model

$SU(2) \times SU(2) \times U(1)$ $\qquad$ $g_0,\ g_2 \ll g_1$



RH Boundary Fermion

LH Boundary Fermion

“Bulk Fermion”

$$\mathcal{L}_f = \varepsilon_L\, M\, \bar\psi_{L0}\Sigma_1\psi_{R1} + M\, \bar\psi_{R1}\psi_{L1} + M\, \bar\psi_{L1}\Sigma_2 \begin{pmatrix}\varepsilon_{tR} & \\ & \varepsilon_{bR}\end{pmatrix} \begin{pmatrix}u_{R2} \\ d_{R2}\end{pmatrix} + h.c.$$

Fermion Structure Motivated by 5-D

Flavor Structure Identical to Standard Model

Particles: photon, W, W’, Z, Z’, t, T, b, B
(c, C, s, S, u, U, d, D & leptons)

Hsin-Chia Cheng

"Universal Extra Dimensions"

Many candidates for new physics have similar signatures at the LHC

- Supersymmetry with R-parity
- Little Higgs Theories with T-parity
- Universal Extra Dimensions (UEDs)

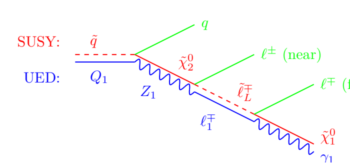
Two robust distinctions between UEDs and SUSY:

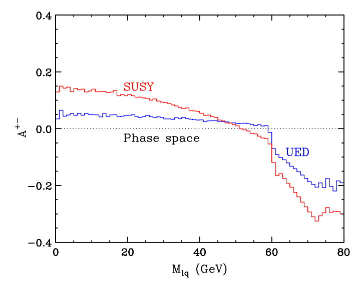
- KK excitations and superpartners have different spin.
- There are higher levels of KK excitations in UEDs.

Need to measure the spin of the produced particles:

Need MC tools which keep spin correlations.

Barr hep-ph/0405052
Smille, Webber, hep-ph/0507170
Datta, Kong, Matchev, hep-ph/0509246





Some public and private tools are available.

More complete MC tools are needed to study and distinguish various possibilities.

Alexander Pukhov

"CalcHEP for beyond Standard Model Physics"

Package for the computation of Feynman diagrams and
integration over multi-particle phase space
event generation and
matrix element generation for other programs.

- From Lagrangians to final distributions with a high level of automation.
- Very flexible with respect to the installation of new models

LanHEP package (*Andrei Semenov*):
Generation of model files, simplifies significantly the construction of lagrangians as e.g. SUSY

Interface
$\longrightarrow$ with `Pythia` via SUSY Les Houches Accord

BSM implementations: MSSM, NMSSM, CP violating MSSM, ED models, LZP model, leptoquark model, Little Higgs model

Shufang Su: "Study Twin Higgs with CompHEP"

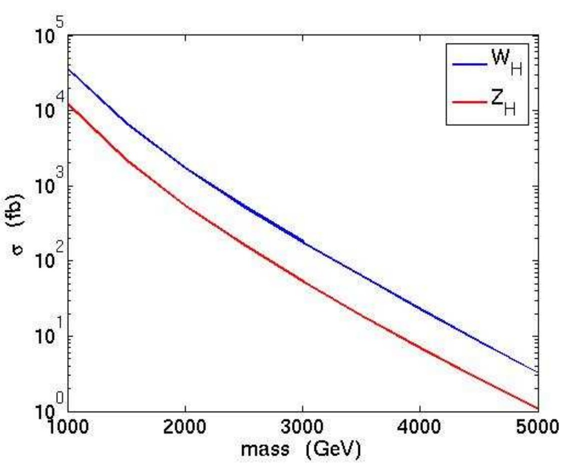
- **Twin Higgs Model: Higgs as pseudo-Goldstone boson**
  Quadratic divergence forbidden by left-right symmetry.

- **New Particles:**
  Heavy gauge boson: WH, ZH; Heavy Top: TH
  Other Higgses: Neutral Higgs Φ^0, Charged Higgs $\Phi^{\pm}$
  Higgs couple to gauge bosons only: $H_1^{\pm}, H_2^0$ (Dark Matter Candidate)

- **Model Parameters:** f_1, (f_2, y), Λ, M, μ, $\sqrt{B}$

- **Using CompHEP** Create Model: Variables, constraints, particles, Lagrangian

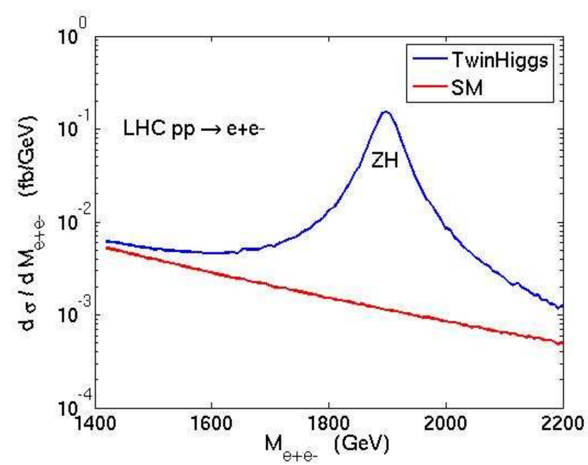
Production cross section



Particle Decays

TH decay	BR
$b\Phi^+$	73.00%
bW^+	16.00%
tZ	6.80%
$t\phi^0$	3.20%
tH	1.10%

Signal/Background



Matt Reece

"Top partners at the LHC: Mass and spin measurement"

Studied Signal: $t'\bar{t}' \to t\bar{t} + 2N$

Implementation in MadGraph

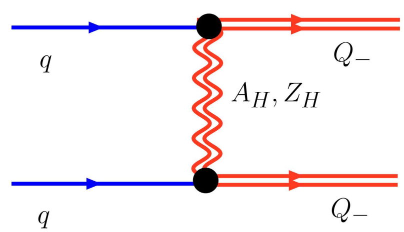
- The signal can be found in the hadronic channel up to high masses
- Masses of t' and N can be found up to discrete degeneracy from spin of t'
- The spin of the t' can be determined (with very high luminosity) from an asymmetry or pseudorapidity correlations sensitive to overall boost
- N spin and couplings are harder: try other asymmetries, spin correlations ...

Alexander Belyaev

“Little Higgs w/ T-parity in CalcHEP”

▷ Complete implementation of LHT in `CalcHEP`: `LanHEP` $\longrightarrow$ `CalcHEP`
Independent implementation was important!

- All signatures relevant for LHC classified
- κ term quark production suggested
- New signatures, incl. LSL have been noticed



- Importance of non-decoupling effects for heavy boson pair production has been shown.
  Heavy boson pair production had been over-estimated previously by a factor 2-5

▷ `CalcHEP-PYTHIA` interface:
go beyond parton level and understand the signal observability - analysis on the way

Jay Hubisz

“Little Higgs w/ T-parity in MadGraph”

MadGraph: calculates arbitrary tree level helicity amplitudes, efficient for $N > 4$

How to input BSM into MadGraph

Fortran code with couplings and widths compiled into `MadGraph`

New Particle: Name-Spin-Mass-Width-Color-PDG Code

Widths needed!

`MadGraph - CalcHEP` interface

input: particles to decay + values of free parameters

output: widths and BRs for requested particles

`MadGraph` modified to read in tables of widths and values of free parameters

Distinguishing models

Generic: Missing energy + cascade decays

distinguishing characteristics: spin and couplings of new particles

`MadGraph` offers comparison of different BSM physics and their collider signatures

spin information is preserved

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- Warped ED *Agashe
- Warped/Comp. Pheno *Sundrum
- UED *Cheng
- KK↔SUSY *Yavin
- Top Partners *Reece
- ...

$\mathcal{L}$

Feynman rules
(Eff. Pot.)

Spectrum Calc

- CPSuperH
- FeynHiggs
- NMHDECAY
- RGE Codes
  Isasusy
  SoftSusy
  Spheno
  SuSpect
  - ...

Flavour Calc

- $(g-2)_\mu$
- $b \to s\gamma$
- $B_s \to \mu^+\mu^-$
- ...

Dark Matter

- micrOMEGAs
- SloopS
- DARKSUSY
- Relic density
- NeutDriver ...

Cross Section Calc

- Tree-level, any
  CalcHEP, *Pukhov,
  CompHEP Belyaev,Su
  Grace-SUSY
  FormCalc
- 1-loop, dedicated
  ILCslepton
  Prospino
  hprod
- 1-loop/General
  Grace-SUSY
  FormCalc
  SloopS
- ...

Decay Codes

- FeynHiggs
- HDECAY
- NMHDECAY
- SDECAY
- SPHENO
- ...

Event Generators

- Isajet
- Pandora *Peskin
- Pythia *Richardson
- Herwig *R,Yavin
- SUSY-MadGraph *Hubisz, Reece
- SUSYGEN - MCFM
- ALPGEN - VECBOS
- WHIZARD ...
- SCET→MC's *Schwartz

Data Analysis Fitters

- Bard *Knuteson,Mrenna
- Fittino
- Sfitter
- NP-LHCFast *Walker
- Requs. from the exp. *de Roeck

SM Bkg/Gen

About Tools

Cross Talks | SLHA

BSM Models

- (N)MSSM
- CPV, RPV
- Ext H, $\tilde{\chi}^0$ sectors *Langacker
- NS Higgses *Kaplan
- Little H *Belyaev, Hubisz,Schmaltz
- Twin Higgs *Su
- Higgsless,Z' *Simmons
- Warped ED *Agashe
- Warped/Comp. Pheno *Sundrum
- UED *Cheng
- KK↔SUSY *Yavin
- Top Partners *Reece
- ...

$\mathcal{L}$

Feynman rules (Eff. Pot.)

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SM Bkg/Gen

Many tools $\rightarrow$ need to unify $\rightarrow$ Accord

The SUSY Les Houches Accord

Interfacing SUSY Spectrum Calculators, Decay Packages and Event Generators

P.Skands, B.C. Allanach, H.Baer, C.Balázs, G.Bélanger, F.Boudjema, A.Djouadi, R.Godbole, J.Guasch, S.Heinemeyer, W.Kilian, J.Kneur, S.Kraml, F.Moortgart, S.Moretti, M.Mühlleitner, W.Porod, A.Pukhov, P.Richardson, S.Schumann, P.Slavich, M.Spira, G.Weiglein

JHEP 0407:036 [hep-ph/0311123]

http://home.fnal.gov/∼skands/slha

What is the SLHA?

SLHA Input

SUSY Models

- MSSM √
- SUGRA √
- GMSB √
- AMSB √
- RPV
- CPV
- FLV
- NMSSM √
- ...

Spectrum Calc

- CPSUPERH
- FeynHiggs √
- ISASUSY √
- NMHDECAY √
- SOFTSUSY √
- SPHENO √
- SUSPECT √ ...

SLHA Input + Spectrum (+ Decay Table)

Event Gen./ Cross Section Calc

- Calc/CompHEP √
- AF's SLEPTONS
- Grace
- HERWIG(++)
- ISAJET
- PROSPINO √
- PYTHIA √
- SHERPA
- SMadgraph
- SUSYGEN
- WHIZARD √ ...

SLHA Input + Spectrum

Dark Matter

- micrOMEGAs √
- DARKSUSY
- NeutDriver
- ...

Decay Codes

- FeynHiggs √
- HDECAY
- NMHDECAY √
- SDECAY √

SLHA Input + Spectrum + Decay Table

$\mathcal{S}$tarting $\mathcal{P}$oint (for the following discussion)

Consistency

Define parameters consistently and unambiguously $\longrightarrow$ specific conventions adopted

Flexible/Extendable

Structure should be general enough to *eventually* handle *any* model $\longrightarrow$ files built of modular data blocks.

Usable

Easy to implement to use $\longrightarrow$ keep basic structure simple.

$\mathcal{W}$hat is needed to 'specify' a $\mathcal{SUSY}$ model

Specify experimental boundary conditions

measured SM gauge g_i^{SM} and Yukawa couplings Y_{ijk}^{SM}

Define the Superpotential

Y_{ijk}, μ (HO: at scale Q, e.g. in the $\overline{\text{DR}}$ scheme) $\rightarrow W$

Define the SUSY breaking terms

Soft breaking gaugino masses M_i, scalar masses m_{ij}, b_{ij}, and trilinear A_{ijk} terms (HO: at scale Q, e.g. in the $\overline{\text{DR}}$ scheme)

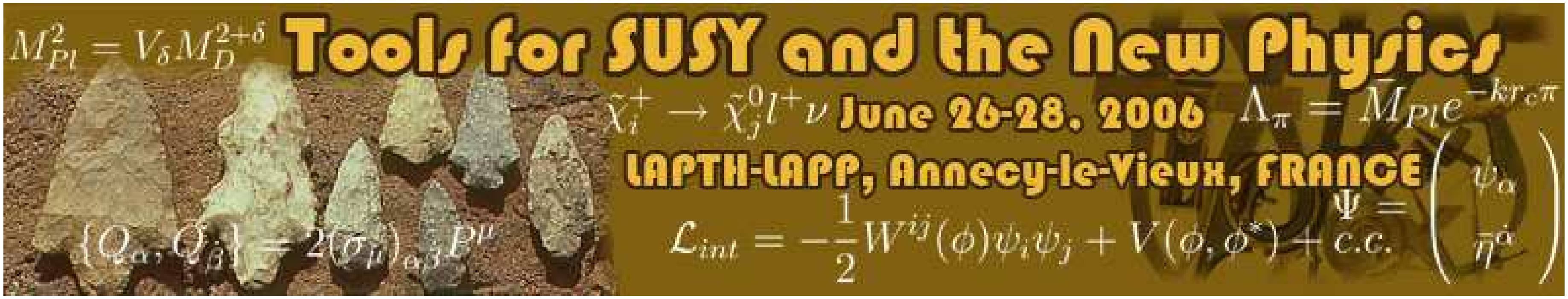
Work out the physical spectrum

Pole masses (for kinematics), and couplings (for ME's), incl. mass $\leftrightarrow$ current eigenstate transl., and for HO calcs. all defs. in a useful and well-defined renormalization scheme/scale.

```
#                                ======================
#                                | THE SDECAY OUTPUT |
#                                ======================
BLOCK DCINFO  # Decay Program information
     1   SDECAY      # decay calculator
     2   1.1a        # version number
BLOCK SPINFO  # Spectrum calculator information
     1   SuSpect     # RGE+Spectrum calculator
     2   2.33        # version number
BLOCK MODSEL  # Model selection
     1     1   mSUGRA model (cMSSM)
BLOCK MINPAR  # Input parameters
         1     1.00000000E+02   # m0
         2     2.50000000E+02   # m_1/2
         3     1.00000000E+01   # tan(beta)
         4     1.00000000E+00   # sign(mu)
         5    -1.00000000E+02   # A0
BLOCK SMINPUTS  # Standard Model inputs
         1     1.27934000E+02   # alpha_em^-1(M_Z)^MSbar
         2     1.16639000E-05   # G_F [GeV^-2]
         3     1.17200000E-01   # alpha_S(M_Z)^MSbar
         4     9.11870000E+01   # M_Z pole mass
         5     4.25000000E+00   # mb(mb)^MSbar
         6     1.78000000E+02   # mt pole mass
         7     1.77700000E+00   # mtau pole mass
...
```

```
#
BLOCK MASS  # Mass Spectrum
# PDG code           mass       particle
        24     8.05247623E+01   # W+
        25     1.11958472E+02   # h
        35     4.04267792E+02   # H
        36     4.03911084E+02   # A
        37     4.12114996E+02   # H+
         5     4.87884274E+00   # b-quark pole mass calculated from mb(mb)_Msbar
   1000001     5.68219389E+02   # ~d_L
   2000001     5.46046688E+02   # ~d_R
   1000002     5.62724463E+02   # ~u_L
   2000002     5.46320906E+02   # ~u_R
...
#
BLOCK NMIX  # Neutralino Mixing Matrix
  1  1     9.86499760E-01   # N_11
  1  2    -5.35875238E-02   # N_12
  1  3     1.45530023E-01   # N_13
  1  4    -5.26081111E-02   # N_14
...
#
BLOCK UMIX  # Chargino Mixing Matrix U
  1  1    -9.18076565E-01   # U_11
  1  2     3.96403104E-01   # U_12
...
```

```
#
BLOCK HMIX Q=  4.65294920E+02  # DRbar Higgs Parameters
         1     3.62362517E+02   # mu(Q)
         2     9.73343673E+00   # tanbeta(Q)
         3     2.44829722E+02   # vev(Q)
         4     1.69925064E+05   # MA^2(Q)
#
BLOCK GAUGE Q=  4.65294920E+02  # The gauge couplings
     1     3.60897241E-01   # gprime(Q) DRbar
     2     6.46514992E-01   # g(Q) DRbar
     3     1.09620534E+00   # g3(Q) DRbar
#
BLOCK AU Q=  4.65294920E+02  # The trilinear couplings
  1  1    -6.70201242E+02   # A_u(Q) DRbar
  2  2    -6.70201242E+02   # A_c(Q) DRbar
...
#                             =================
#                             |The decay table|
#                             =================
...
#         PDG            Width
DECAY   1000021     4.46580230E+00   # gluino decays
#          BR          NDA      ID1       ID2
     2.12433782E-02    2     1000001        -1   # BR(~g -> ~d_L  db)
     2.12433782E-02    2    -1000001         1   # BR(~g -> ~d_L* d )
     5.10105203E-02    2     2000001        -1   # BR(~g -> ~d_R  db)
...
```



Aim

review main calculational tools, including generators & Monte-Carlos

for BSM particle searches

at present & future colliders

and in non collider physics experiments ($\to$ DM searches)

Talks

Discussion Sessions

Round tables:

how to improve the existing programs

how to incorporate different existing constraints

how best present future data

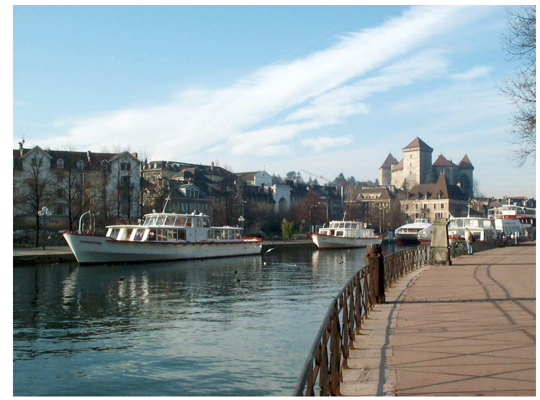
how modules from different codes can be sewn together and interchanged

http://lappweb.in2p3.fr/TOOLS2006

tools06@lapp.in2p3.fr

MC4LHC 17-26 Jul 2006, CERN/Geneva

Conclusions



Thanks to the Organizers!

See you in Annecy!